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EFFECT OF SIGNAL JITTER ON THE SPECTRUM OF ROTOR IMPULSIVE NOISE

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Abstract

The effect of randomness or jitter of the acoustic waveform on the spectrum of rotor impulsive noise is studied, because of its importance for data interpretation. An acoustic waveform train is modelled representing rotor impulsive noise. The amplitude, shape, and period between occurances of individual pulses are allowed to be randomized assuming normal probability distributions. Results, in terms of the standard deviations of the variable quantities, are given for the autospectrum as well as special processed spectra designed to separate harmonic and broadband rotor noise components. Consideration is given to the effect of accuracy in triggering or keying to a rotor one per revolution signal. An example is given showing the resultant spectral smearing at the high frequencies due to the pulse signal period variability.

Nomenclature

b	number of blades per rotor, integer
C_m	magnitude of P_m
$E[Arg]$	expected value of argument
f_m	$= m\Delta f$, frequency of m-th analysis band, sec^{-1}

$\Delta f = 1/T$,	frequency bandwidth, sec^{-1}
G_m	one-sided autospectral function, Eq 2, $sec \cdot Pa^2$
$(G_m)_r$, $(G_m)_d$	see Eqn. 14
i	pulse identifier in time records, integer
j	$\sqrt{-1}$
k	identifier of data sample, each sample of length T, integer
k_o	total number of data samples, integer
ℓ	number of rotor periods per sample period, integer
m,n	integers
N	sample size, generally equals an integer power of 2
$p(t)$	acoustic pressure time history, Pa
p_n	$= p(n\Delta t)$, data sequence representing $p(t)$, Eq. 1
$P(f)$	Fourier transform of $p(t)$, $sec \cdot Pa$
P_m	$= P(f_m)$, discrete Fourier transform sequence, Eq. 1
Δt	digitization time interval of $p(t)$ data, sec
T	$= N\Delta t$, sample record length, sec
T_o	reference time in sample pressure history records, sec
T_r	rotor period of rotation, sec
σ_x	standard deviation of variable x
τ	variation of pulse occurrence time, sec
Φ_m	phase of P_m, rad

Subscripts and Superscripts

${}_k^iP_m$, ${}_k^iC_m$, ${}_k^i\Phi_m$	value of terms for m-th frequency band for the particular i-th pulse of the k-th record sample. When term is averaged over k_o samples, "a" replaces "k". When "i" or "k" is removed, term is independent of these.
${}_k^i\tau$	variability for i-th pulse of the k-th record sample

Introduction

The study of helicopter impulsive noise involves analysis of acoustic pressure time histories and associated spectra. For a discrete noise source such as blade-vortex interaction (BVI), the acoustic pressure pulses in the time histories can be randomized somewhat in amplitude and phase with respect to the blade passages. This occurs even in well controlled wind tunnel environments, where microphones are fixed with respect to model rotor hub positions, because of unsteadiness or jitter in blade motion and blade tip vortex trajectory. This jitter causes spectral smearing and a broadband appearance of the higher harmonics. This can make it difficult to identify in an autospectrum the discrete and truly broadband (turbulence caused) noise source contributions [1]. In addition, jitter presents a major problem for a common analysis procedure employed to "clean-up" acoustic pressure time histories [2]. The procedure involves averaging time histories, in a manner which is keyed to the shaft position (such as through a one-per-revolution signal), to remove broadband noise resulting in smooth acoustic pressure signatures. Conceptionally spectra corresponding to these averaged signatures would represent the "discrete" contribution to the total autospectra. However this averaging procedure can render signatures of noticeably distorted shape and decreased amplitude unless jitter is small. This concern has prompted caution in the selection of test conditions to analyze in this manner. Wisely still more caution has been exercised in presentation of special "discrete" spectra, being without the benefit of a quantitative understanding of the effect of jitter on the spectra.

It is the purpose of this paper to provide a diagnostic tool by quantifying the effect of impulse signal jitter on the narrowband auto-spectra. The effect of jitter on special spectral processing, intended for separating the discrete from broadband components, is also considered.

Digital Processing and Terminology

Digital procedures [3,4] for data processing require that acoustic pressure time histories p(t) be sampled at points Δt apart. The record length becomes $T = N\Delta t$ where N is the sample size (typically 1024). The continuous p(t) is replaced by the data sequence $\{p_n\} = \{p(n\Delta t)\}$ for $n = 1, 2, 3, \ldots N$. Also replacing a continuous transform P(f) is a discrete Fourier transform sequence $\{P_m\} = \{P(m\Delta f)\} = \{P(f_m)\}$ for $m = 1, 2, 3, \ldots N$. Here $\Delta f = 1/T$ which is the minimum bandwidth resolution. The sample size N induces a Nyquist cutoff or folding frequency given by $f_c = 1/2\Delta t$. Prior to digital conversion p(t) is normally low-pass filtered below f_c to prevent serious aliasing errors. With $2\Pi(m\Delta f)n\Delta t = 2\Pi mn/N$

$$P_m = P(f_m) = \Delta t \sum_{n=1}^{N} p_n \exp(-j2\Pi mn/T), \quad m = 1, 2, 3, \ldots N$$

and (1)

$$p_n = p(n\Delta t) = \Delta f \sum_{m=1}^{N} P_m \exp(j2\Pi mn/T), \quad n = 1, 2, 3, \ldots N$$

which are Fourier transform pairs. It is seen that the data is treated as if they were periodic data of period T. From the above P_m, the one-sided autospectral density function is

$$G_m = G(m\Delta f) = \frac{2}{T} E\,[P_m^* P_m]$$

$$\doteq \frac{2}{k_o T} \sum_{k=1}^{k_o} \left| {}_kP_m \right|^2 = \frac{2}{k_o T} \sum_{k=1}^{k_o} {}_kP_m^* \, {}_kP_m \tag{2}$$

Here E[ ] is the expected value of the argument and k represents the particular data sample each of length T. The total number of averages k_o is assumed to be large for the estimate to minimize statistical error.

Impulsive Noise Transform Decomposition

Figure 1 illustrates two sample acoustic pressure time histories with four pulses in each waveform. This can be representative of a four bladed rotor producing BVI, thickness, and/or loading noise. The samples shown are keyed to a rotor one-per-revolution signal so each t corresponds to the rotor at a particular azimuthal position. Each pulse, identified by the "i" notation, can be arbitrary in shape although similar pulses are shown. Presentations are also possible for a "b" bladed rotor where the sample period is $T = \ell T_r$, T_r being the rotor period of rotation. The number of pulses seen then would be $b\ell$ rather than 4 for each sample. As shown in Figure 1, variation in amplitude and time spacing can occur between the different samples. What is desired is to find the spectral consequences of such signal "jitter" between samples.

The first step in the analysis is illustrated in Figure 2 where the ${}_kp(t)$ sample of Figure 1 is decomposed into 4 (or $b\ell$) separate pulse histories, i.e.

$${}_kp(n\Delta t) = \sum_{i=1}^{4} {}_k^ip(n\Delta t)$$

The history ${}^{1}_{k}p(n\Delta t)$ is taken as a pulse signature located at nominal (or average) time T_o with a possible variation of ${}^{1}_{k}t$. For the moment T_o is assumed constant for perfect keying to a one-per-rev signal. The history ${}^{2}_{k}p(n\Delta t)$ is that pulse at an average time of $T_o + T/4$ with variation ${}^{2}_{k}\tau$. The same follows with ${}^{3}_{k}p(n\Delta t)$ and ${}^{4}_{k}p(n\Delta t)$ with average spacing T/4 and variations ${}^{i}_{k}\tau$. The corresponding transforms are from Equation (1)

$$ {}_{k}P_{m} = \sum_{i=1}^{4} {}^{i}_{k}P_{m} = \sum_{i=1}^{4} {}^{i}_{k}C_{m} \exp[-j\,{}^{i}_{k}\phi_{m} - j2\Pi f_{m}(T_{o} + \frac{(i-1)T}{4} + {}^{i}_{k}\tau)] \qquad (3) $$

which follows from the fact that $p(t - t_0)$ gives a transform $P(f)\exp[-j2\Pi f t_0]$. Equation (3) explicitly accounts for transform phase shifting corresponding to pressure data time shifting. The terms ${}^{i}_{k}C_{m}\exp[-j\,{}^{i}_{k}\phi_{m}]$ are Fourier coefficients specifying the shape and amplitude of the k-th sample of the i-th pulse. The positive magnitude ${}^{i}_{k}C_{m} = |{}^{i}_{k}P_{m}|$ and the phase denoted by ${}^{i}_{k}\phi_{m}$. For the general case of a presentation of "ℓ" periods for a "b" bladed rotor, one replaces the number 4 in Equation (3) by $b\ell$ in the two places appearing. Note then that $f_m = m/T = m/\ell T_r$; so if the number of revolutions analyzed ℓ is say 2 then f_m equals one-half that for $\ell=1$ thereby reducing the bandwidth by a factor of two.

Spectrum for No Jitter Case

For the limiting case where there is no jitter in amplitude or time for the signals, ${}^{i}_{k}\tau = 0$ and ${}^{i}_{k}C_{m}\exp[-j\,{}^{i}_{k}\phi_{m}] = {}^{i}C_{m}\exp[-j\,{}^{i}\phi_{m}]$ for all samples k. It is further assumed for this example that the pulses are identical in shape and amplitude, i.e. ${}^{i}C_{m}\exp[-j\,{}^{i}\phi_{m}] = C_{m}\exp[-j\phi_{m}]$ for all pulses i.

From Equation (3)

$$P_m = \sum_{i=1}^{b\ell} C_m \exp\left[-j\phi_m - j2\pi f_m\left(T_o + \frac{(i-1)T}{b\ell}\right)\right]$$

$$= b\ell C_m \exp[-j\phi_m - j2\pi f_m T_o] \quad \text{for } m = b\ell, 2b\ell, 3b\ell, \ldots$$

$$= 0 \quad \text{for } m \neq b\ell, 2b\ell, 3b\ell, \ldots$$

It is seen that a nonzero contribution is obtained only for frequencies that are multiples of f_b, where $f_b = b\ell/T = b/T_r$ which is the blade passage frequency. The auto-spectrum corresponding to P_m is, from Equation (2),

$$G_m = \frac{2}{T}(b\ell\ C_m)^2 \quad \text{for } m = b\ell, 2b\ell, 3b\ell, \ldots$$
$$= 0 \quad \text{for } m \neq b\ell, 2b\ell, 3b\ell, \ldots \tag{4}$$

Spectrum for a Normal Proability Distribution of Jitter

Now considering the more general case where jitter is present, from Equation (2) and (3)

$$G_m = \frac{2}{T}\frac{1}{k_o}\sum_{k=1}^{k_o} {}_kP_m^*\ {}_kP_m$$

$$= \frac{2}{T}\frac{1}{k_o}\sum_{k=1}^{k_o}\sum_{i=1}^{b\ell}\sum_{i'=1}^{b\ell} {}_k^iC_m\ {}_k^{i'}C_m \exp\left[-j({}_k^{i'}\phi_m - {}_k^{i}\phi_m) - j2\Pi f_m\left(\frac{(i'-i)T}{b\ell} + ({}_k^{i'}\tau - {}_k^{i}\tau)\right)\right]. \tag{5}$$

This equation for G_m is now evaluated by assuming pulse amplitude, shape, and time of occurrence are all random variables. The term $[{}_k\overset{*}{P}_m\ {}_kP_m]$ is a function of ${}_k^iC_m$, ${}_k^i\phi_m$, and ${}_k^i\tau$. For the moment call these $\underset{\sim}{x}_1$, $\underset{\sim}{x}_2$, and $\underset{\sim}{x}_3$ respectively, each representing $b\ell$ random variables (for example $\underset{\sim}{x}_1 = [{}_k^1C_m, {}_k^2C_m, \ldots, {}_k^{b\ell}C_m]$).

For large k_o

$$\frac{1}{k_o}\sum_{k=1}^{k_o}[{}_kP_m^*\ {}_kP_m] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[P_m^*P_m]\ p(\underset{\sim}{x}_1, \underset{\sim}{x}_2, \underset{\sim}{x}_3)d\underset{\sim}{x}_1\ d\underset{\sim}{x}_2\ d\underset{\sim}{x}_3 \tag{6}$$

The $p(\underset{\sim}{x}_1, \underset{\sim}{x}_2, \underset{\sim}{x}_3)$ term is the joint probability density. It is now assumed that $\underset{\sim}{x}_1$, $\underset{\sim}{x}_2$, and $\underset{\sim}{x}_3$ variations are uncorrelated and additionally that their variations all have normal or Gaussian distributions, i.e.

$$p(\underset{\sim}{x}_1, \underset{\sim}{x}_2, \underset{\sim}{x}_3) = \prod_{i=1}^{b\ell} p({}^{i}_{k}C_m) \cdot \prod_{i'=1}^{b\ell} p({}^{i'}_{k}\Phi_m) \cdot \prod_{i''=1}^{b\ell} p({}^{i''}_{k}\tau) \tag{7}$$

where for each component of $\underset{\sim}{x}_1$, $\underset{\sim}{x}_2$, and $\underset{\sim}{x}_3$

$$p(x) = \frac{1}{\sigma_x \sqrt{2\Pi}} \exp[-(x - x_o)^2/2\, \sigma_x^{\,2}]. \tag{8}$$

Here σ_x is the standard deviation of x and x_o is the mean value of x, i.e.

$$x_o = E[x] = \int_{-\infty}^{\infty} x\, p(x)\, dx \tag{9}$$

and

$$\sigma_x^{\,2} = E\,[(x - x_o)^2] = E\,[x^2] - x_o^{\,2}. \tag{10}$$

It is acknowledged that the properties assumed in Equations (7) and (8) are restrictive in allowable pulse behavior. It does, however, permit a solution believed to be realistic in practice.

It is seen from Equations (6) and (7) that G_m of Equation (5) can be evaluated by the individual determinations of the expected values of the separate terms. First employing Equations (9) and (10)

$$\begin{aligned} E\,[{}^{i}C_m \; {}^{i'}C_m] &= {}^{i}_{a}C_m^2 + \sigma_{{}^{i}C_m}^{\,2}\,, \text{ if } i = i' \\ &= {}^{i}_{a}C_m \; {}^{i'}_{a}C_m \;, \text{ if } i \neq i' \end{aligned} \tag{11}$$

where ${}^{i}_{a}C_m = E\,[{}^{i}C_m] = \frac{1}{k_o} \sum_{k=1}^{k_o} {}^{i}_{k}C_m$ which is the average amplitude of the coefficient and the σ-term is the standard deviation of ${}^{i}C_m$.

Next for the phase

$$E\,[\exp[-j({}^{i'}\phi_m - {}^{i}\phi_m)]] = 1 \text{ if } i = i' \tag{12}$$
$$= \exp[-j({}^{i'}_{a}\phi_m - {}^{i}_{a}\phi_m)]\ \exp\left[-\frac{1}{2}\left(\sigma_{i'_{\phi_m}}^{2} + \sigma_{i_{\phi_m}}^{2}\right)\right]$$
$$\text{if } i \neq i'$$

where ${}^{i}_{a}\phi_m$ is the average phase of the coefficient and the σ-term its standard deviation. Finally for the time jitter term

$$E\,[\exp(-j2\Pi f_m({}^{i'}\tau - {}^{i}\tau))] = 1 \text{ if } i = i' \tag{13}$$
$$= \exp\left[-\frac{1}{2}(2\Pi f_m)^2\left(\sigma_{i'_{\tau}}^{2} + \sigma_{i_{\tau}}^{2}\right)\right]$$
$$\text{if } i \neq i'.$$

Now inserting the results of Equations (11) - (13) into Equation (5) and rearranging one obtains

$$G_m = (G_m)_r + (G_m)_d \tag{14}$$

where

$$(G_m)_r = \frac{2}{T}\sum_{i=1}^{b\ell} {}^{i}_{a}C_m^2\,[1 + (\sigma_{i_{C_m}}^{2}/{}^{i}_{a}C_m^2) - \exp[-\sigma_{i_{\phi_m}}^{2} - (2\Pi f_m\,\sigma_{i_{\tau}})^2]]$$

and

$$(G_m)_d = \frac{2}{T}\sum_{i=1}^{b\ell}\sum_{i'=1}^{b\ell} {}^{i}_{a}C_m\ {}^{i'}_{a}C_m\ \exp\left[-j({}^{i'}_{a}\phi_m - {}^{i}_{a}\phi_m) - j2\Pi\,\frac{(i'-i)T}{b\ell}\right]$$
$$\cdot \exp\left[-\frac{1}{2}\left(\sigma_{i'_{\phi_m}}^{2} + \sigma_{i_{\phi_m}}^{2}\right) - \frac{1}{2}(2\Pi f_m)^2\left(\sigma_{i'_{\tau}}^{2} + \sigma_{i_{\tau}}^{2}\right)\right].$$

This is the resultant autospectrum where the statistics of jitter are defined in terms of the standard deviation of the variable quantities - pulse time, amplitude, and shape. The term $(G_m)_d$, defines a so-called "discrete" portion whereas $(G_m)_r$ defines a "random" portion of G_m. This is dealt with below.

Special Processing

In the proceeding analyses T_o of Equation (3) is assumed constant for clarity of presentation. However, even if data samples were not perfectly (or at all) keyed to a rotor one-per-rev signal through say triggering error and thus T_o would be variable between samples k, i.e. $T_o = {}_kT_o$ in Equation (3), it is readily shown that Equation (14) for G_m is unchanged.

Such keying, however, would have impact on certain alternate spectral definitions one might employ to study particular noise mechanisms. Of interest is the spectra corresponding to averaged time histories. As indicated in the introduction, such spectra may be produced with the intent to remove broadband noise content. This "discrete" or deterministic spectrum, call this $(G_m)_d'$, is found to be

$$
\begin{aligned}
(G_m)_d' &= \frac{2}{T} \left| E\ [P_m] \right|^2 \\
&= (G_m)_d \exp\ [-(2\Pi f_m \sigma_{T_o})^2]
\end{aligned}
\tag{15}
$$

where σ_{T_o} is the standard deviation of T_o (assuming normal and independent variability) and $(G_m)_d$ is that from Equation (14). In parallel one can define a "random" spectrum $(G_m)_r'$ equal

$$
\begin{aligned}
(G_m)_r' &= \frac{2}{T} E \left| P_m - E[P_m] \right|^2 \\
&= G_m - (G_m)_d'
\end{aligned}
\tag{16}
$$

where G_m is that from Equation (14). So only when variations in T_o are minimized do $(G_m)_d' = (G_m)_d$ and $(G_m)_r' = (G_m)_r$. It is seen that Equations (15) and (16) relate the degree of success one can have in processing to separate "discrete" from "random" noise, to the extent such success depends on keying accuracy. Equation (14) can be employed to help determine to what degree one can utilize the results, even with accurate keying, for any physical interpretation of the separation spectral data.

Example

The spectrum for a signal with jitter is now compared to that spectrum obtained for an ideal case where there is no jitter. For the no jitter case, all σ's are zero and if the pulses are identical for different i's then Equation (14) renders Equation (4). For the comparison it is assumed for the jitter case that all pulses are of the same average shape, i.e. ${}^{i}_{a}C_m \exp[-j\,{}^{i}_{a}\phi_m] = {}_{a}C_m \exp[-j\,{}_{a}\phi_m)$. Additionally, it is assumed any amplitude variations are uniform for each pulse so no shape charges occur, only overall amplitudes, i.e. $\sigma_{{}^{i}C_m}/{}^{i}C_m$ is constant (say σ_C/c) and $\sigma_{{}^{i}\phi_m} = 0$. Also the time variability for the different pulses i are the same, so $\sigma_{i_\tau} = \sigma_\tau$. So for the jitter case from Equation (14)

$$G_m = (G_m)_d + (G_m)_r \tag{17}$$

$$(G_m)_r = \frac{2}{T} b\ell\,{}_aC_m^2[1 + (\frac{\sigma_c}{c})^2 - \exp\,[-(2\Pi f_m\sigma_\tau)^2]]$$

and

$$(G_m)_d = \frac{2}{T}(b\ell\,{}_aC_m)^2 \exp\,[-(2\Pi f_m\sigma_\tau)^2] \text{ for } m = b\ell,\ 2\,b\ell,\ 3\,b\ell,\ \ldots$$

$$=0 \qquad \text{for } m \neq b\ell,\ 2\,b\ell,\ 3\,b\ell,\ \ldots$$

These spectra and that of Equation (4) are presented in Figure 3 for the first m = 34 frequency bands. The levels are normalized in each band by $2(b\ell\,{}_aC_m)^2/T$ which correspond, at harmonics of f_b, to the levels of G_m for the ideal case of no jitter (Equation (14)). The data period T is taken as equal to the rotor period T_r (ℓ=1), the number of rotor blades are four (b=4), and the time variability is large at $\sigma_\tau/T = 0.01$. For clarity, the amplitude variability σ_c is assumed zero so only the effect of σ_τ is shown. In general the σ_c contribution to the comparison would be $10 \log [(\sigma_c/c)^2/b\ell]$. For the present $b\ell=4$ case, a value of $\sigma_c/c=0.5$ would render a -12dB contribution for all m bands.

Figure 3 shows the effect of pulse time jitter to be significant for the spectrum G_m. The levels of the individual blade passage harmonics are substantially reduced and the spectra becomes broadband in appearance with levels approaching -6 dB ($-10 \log b\ell$) below the no jitter case for large m. Note in this normalized presentation that the integrated levels for the spectra with and without jitter are equal, promoting the view that jitter merely shifts the spectral energy content from the harmonics of f_b to the side bands. However, this does not strictly hold, for as indicated in Equation (17) for the unnormalized G_m, the level of each band m is governed by the coefficient amplitude ${}_aC_m$ for that band, not that of the nearest band corresponding to a harmonic of f_b.

Conclusions

The present results explain quantitatively the spectral smearing which occurs when simple jitter is present in the acoustic signals. The results can be applied diagnostically in the identification and separation of source contributions to the rotor noise spectra. Applicability of the present equations is direct when discrete or impulsive noise dominates the noise field. In the presence of additional discrete noise with differing pulse shape and jitter statistics, as well as the presence of substantial broadband noise, a precise analysis requires additional steps. Here appropriate terms can be readily added to the modelled pressure transform ${}_kP_m$ of Equation (3) prior to determining the autospectrum or special spectra processed for diagnostic purposes.

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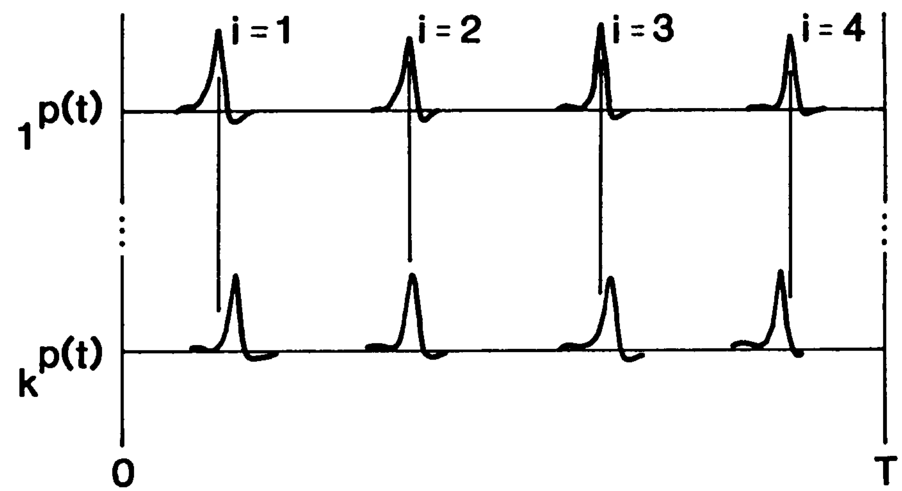

Figure 1 - Sample acoustic pressure time histories keyed to the rotor period of rotation

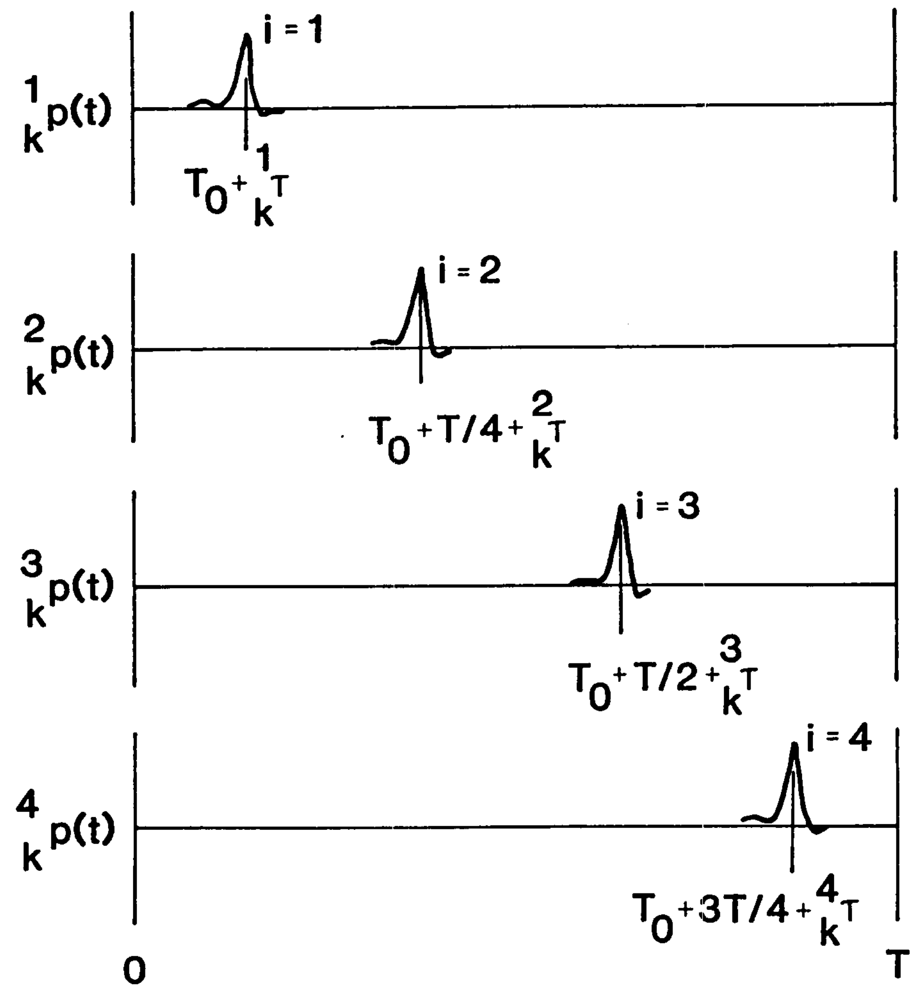

Figure 2 - Decomposition of impulsive acoustic pressure time history of ${}_kp(t)$ for a four-bladed rotor

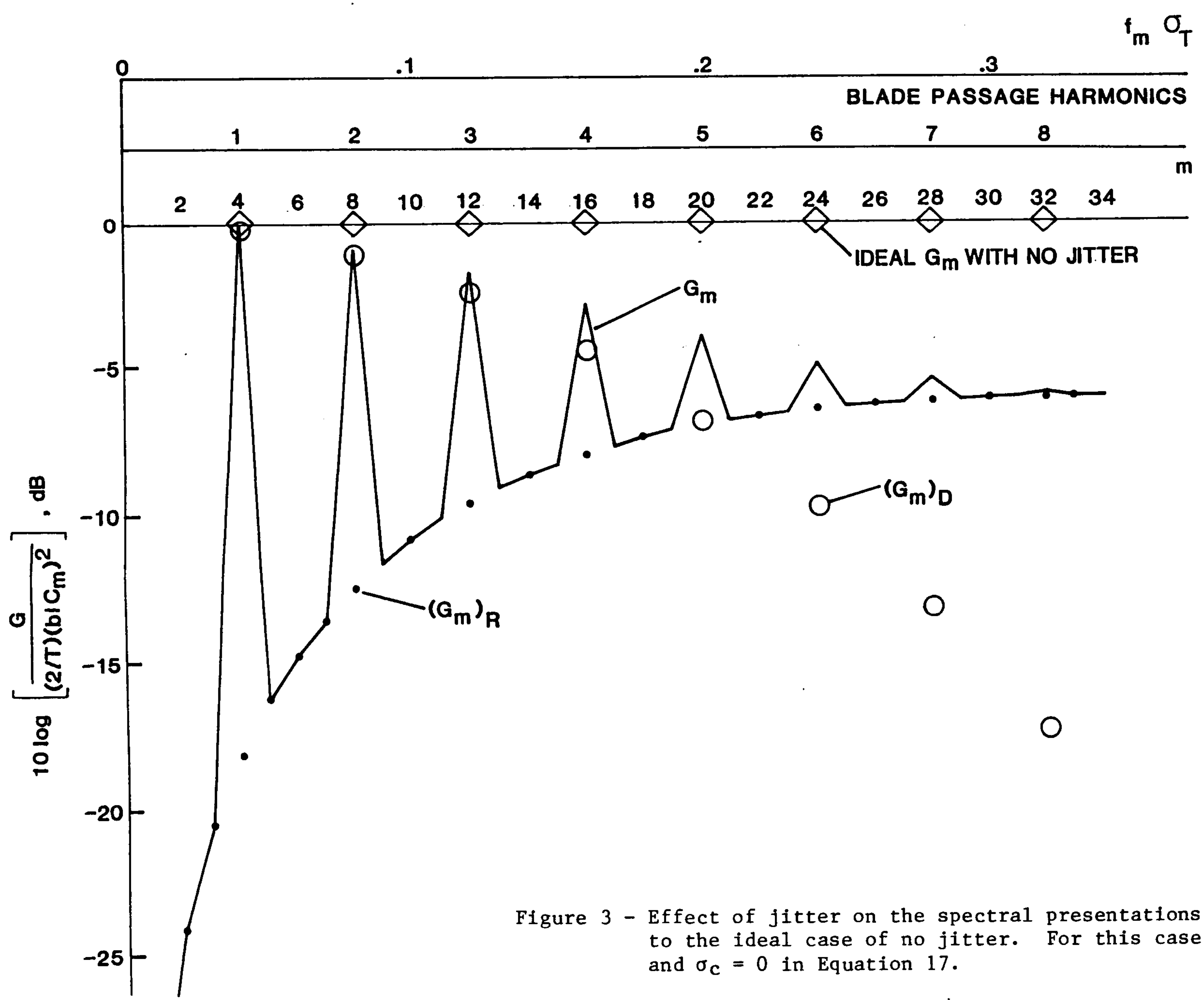

Figure 3 - Effect of jitter on the spectral presentations referenced to the ideal case of no jitter. For this case $\sigma_\tau/T = 0.01$ and $\sigma_c = 0$ in Equation 17.

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16. Abstract

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